CHARACTERISTICS AND PERFORMANCE
OF A DEEP OCEAN DISPOSAL SYSTEM
FOR LOW-PURITY CO₂ GAS BY GAS LIFT EFFECT

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ABSTRACT

Progressive Gas Lift Advanced Dissolution (P-GLAD) system has been newly developed to mitigate the global warming. The system dissolves low-purity CO_2 gas in seawater at shallow portions and sequestrates CO_2 at the deep ocean. The system is an inverse-J pipeline set in the ocean between 200 and 3000m in depth. Usual methods of deep-sea sequestration such as storage of liquid CO_2 at the deep-sea floor and deep-sea releasing of liquid CO_2 consume huge amount of energy, because these need high-purity capture and liquefaction of CO_2. To realize deep-sea sequestration with low energy consumption and low environmental impact, we utilize a gas-lift effect to dissolve low-purity CO_2 into seawater and transport CO_2 solution to a great depth. The present paper describes basic characteristics and performance of the system for low-purity CO_2 gases. We also discuss cost estimate including a system for capture of CO_2 gas and construction of P-GLAD.

INTRODUCTION

The global warming mainly due to the increase of atmospheric CO_2 concentration is getting serious. A countermeasure that can economically and effectively treat huge amount of CO_2 (23GtC/year) emitted by human activities should be developed. Ocean sequestration of CO_2 is a hopeful option to mitigate the increase in the atmospheric CO_2 concentration, because the ocean has been absorbing and sequestrating CO_2 through the history of the earth, and the absorption capacity is enormous [Hoffert, 1979]. Several ideas of ocean disposal of CO_2 have been proposed. They are categorized as follows: a) storage of liquid CO_2 on the deep-sea floor deeper than about 3000m, in the idea CO_2 is stored on the deep sea flow as CO_2 ponds covered with CO_2 gas hydrate [Ohsumi, 1993]; b) direct release of liquid CO_2 into the intermediate depth water of 1000-3000m [Liro, 1992]; c) direct release of gaseous CO_2 into shallow water and use of gravity current [Haugan, 1992], the idea is direct release of gaseous CO_2 into the seawater at a depth of 200-400m and expecting sink of CO_2-rich seawater to the deep-sea by the density difference between the solution and ambient seawater.
Long term isolation, more than several hundreds years, of CO_2 from the atmosphere is expected in the methods a) and b), because the initial injection point is in intermediate or deep water. Though deeper initial injection assures longer-term isolation, these two methods need high-purity capture and separation, and liquefaction of CO_2. Higher-purity separation of CO_2 from exhausted gas consumes larger energy. They inevitably consume huge amount of extra energy in these preprocessing. The deep initial injection brings the deep ocean secondary environmental impact, namely acidity by dense CO_2 solution. Since the method c) need no liquefaction, it improves an amount of energy consumption. Density and/or temperature layers in the ocean, which grow in middle and low latitude area, prevent sinking of CO_2 solution to a great depth. In this case, long-term isolation is no longer expected.
A method of the ocean sequestration has to isolate huge amount of CO_2 from the atmosphere for long term, several hundreds or thousand years, with low cost, low energy consumption and low environmental impact. To realize this, the preprocessing should be low-purity separation and no

liquefaction; besides the disposal method should be able to deal with low-purity CO_2 gas. We have been improving GLAD system, which is an ocean sequestration system for pure CO_2 gas using gas lift effect [Saito, 1996; Saito 1997; Saito, 2000; Kajishima, 1995; Kajishima, 1997]. We have developed P-GLAD (Progressive Gas Lift Advanced Dissolution, See Fig.1) system [Saito, 1999a, b] for low-purity CO_2 gas. In the present paper, we discuss performance, cost estimate and environmental receptivity of P-GLAD by experimental and numerical simulation. First, we describe experimental results on solubility and pumping performance of the system. Second, essence of numerical method is explained. Agreement of numerical results with experimental ones is discussed. Third, acidity of the solution released from the system is discussed. Finally, based on these discussions cost estimate for P-GLAD and comparison of the cost with usual method are performed.
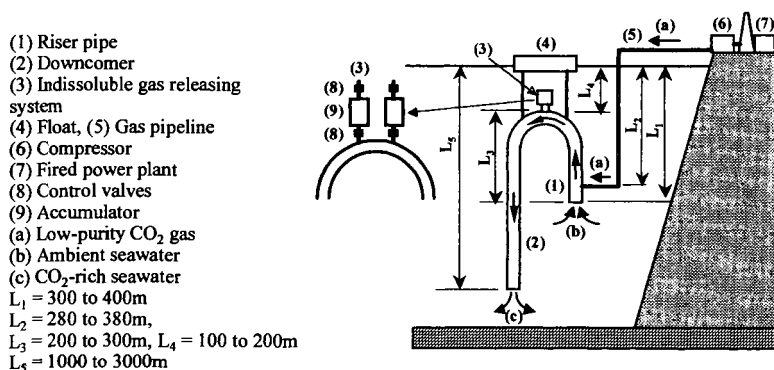
EXPERIMENT

Experimental setup used in the present investigation, a laboratory-scale P-GLAD system, is illustrated in Fig. 2. The riser pipe (1) and the downcomer (2) are made of acrylic transparent pipes of 25mm in diameter and 7.69m in height. The riser is connected to two pressure vessels (4) made of stainless pipe of 106.3mm in diameter and 8.19m in height. The downcomer is placed inside the vessel. The top of the riser is equipped with an indissoluble gas-releasing device (3), which releases indissoluble gases of N_2 and O_2. Low-purity CO_2 gas, mixture of pure CO_2 gas (99.9% purity) and pure air (CO<1ppm, CO_2<1ppm and CH_4<1ppm) well mixed in a gas-mixing accumulator (10), is injected into the riser through a gas injector (5). The gas-injector has an annular structure; the inner pipe of acrylic resin with 25mm in diameter is equipped with 108 small capillaries of 0.78mm in diameter; outer pipe is made of stainless steel of 106.3mm in diameter.

Tap water is supplied at the top of each pressure vessel after filtration by a 1μm filter. Our experiments were performed under overflowing condition. The temperatures of the supplied water and the gas-liquid mixtures were between 287 and 290K.

MESUREMENT

Superficial velocity of the liquid phase J_L was measured using an electromagnetic flowmeter (A), the temperature and static pressure in the riser using thermo couples (B) and pressure transducers (C), respectively. We measured and controlled mass flow rate of each gas, Q_{CO2} and Q_{AIR} using mass flow controllers (E) and (F).

Performance of solubility of the laboratory-scale P-GLAD is calculated from CO_2 molar concentration of the gas phase in the riser [Saito, 1999a]. First, we visualized and recorded the bubbly flows in the riser using two sets of high-speed video systems of 500 frames/s and stroboscopes of 10μs of flushing rate (C). Second, we analyzed the images by digital image processing. Third, bubble characteristics such as volume, surface area, location and velocity are calculated from the processing results. Finally, the molar concentration and solubility were calculated from the above characterization of bubbles.

(1) Riser pipe
(2) Downcomer
(3) Indissoluble gas releasing system
(4) Float, (5) Gas pipeline
(6) Compressor
(7) Fired power plant
(8) Control valves
(9) Accumulator
(a) Low-purity CO_2 gas
(b) Ambient seawater
(c) CO_2-rich seawater
L_1 = 300 to 400m
L_2 = 280 to 380m,
L_3 = 200 to 300m, L_4 = 100 to 200m
L_5 = 1000 to 3000m

The main part of the P-GLAD system is an inverse-J pipeline (1) and (2), and an indissoluble gas releasing system (3). The low-purity CO_2 gas (a) is injected into the riser pipe (1) at a depth between 200 and 400m. An upward current occurs in the pipe by a gas-lift effect. CO_2 included in the bubbles dissolves into seawater while the bubbles rise in the riser. Ambient seawater (b) is flowing at the bottom of the riser. Indissoluble gas of N_2 is released at the top of the riser by an indissoluble gas releasing system (3). The downcomer (2) is used as a transportation pass of the CO_2-rich seawater (c) to a great depth between 1000 and 3000m. An additional downward current is generated in the downcomer owing to the density difference between the CO_2-rich and ambient seawater. Thus, the bubble dissolution and the transportation of CO_2-rich seawater to great depths are enhanced in the P-GLAD system by the gas lift effect.

Fig.1 Concept and principle of the P-GLAD system

(1) Dissolution pipe
(2) Drainpipe
(3) Indissoluble gas releasing device
(4) Pressure vessels
(5) Gas injector
(6) Observing windows
(7) Camera lifter
(8) CO_2-gas cylinder
(9) Pure-air cylinder
(10) Gas mixing accumulator

(A) Electromagnetic flowmeter
(B) Thermo couplers
(C) Pressure transducers
(D) High-speed video systems & strobes
(E) & (F) Mass flow controller

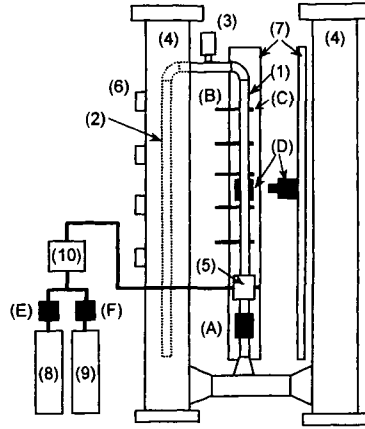Fig. 2 Experimental setup

NUMERICAL SIMULATION

The Lagrange method was applied for the each bubbles, and the Euler method for the liquid phase. Conservation lows of mass and momentum for each phase were employed. Trapp & Mortensen scheme was used in our computation [Trapp, 1993]. In the present investigation, applying the Lagrange method mass conservation low of dispersed gas phase is expressed as following equation.

$$\frac{d}{dt}(\rho_p V_p) = -k_L M_p (C_s - C) A_p \tag{1}$$

where k_L represents the mass transfer coefficient, $V_p (= 4\pi r_p^3/3)$ the bubble volume, $A_p (= 4\pi r_p^2)$ the surface area, and r_p the equivalent diameter of bubble. Density of gas phase ρ_p is calculated from the ideal gas equation. C_s is the molar concentration of CO_2 on the bubble surface and defined as saturated concentration of CO_2 calculated from Henry's low. C is the molar concentration of CO_2 in the solution, estimated by the equation of convective diffusion.

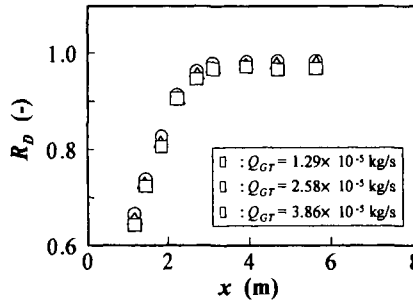$$\frac{dC}{dt} + J_l \frac{dC}{dx} = D_T \frac{d^2 C}{dx^2} + q_R \tag{2}$$

Fig. 3 Axial profiles of dissolution ratio in the riser. $Q_{GT} = Q_{CO2} + Q_{AIR}$
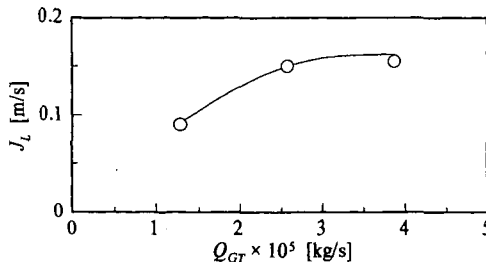

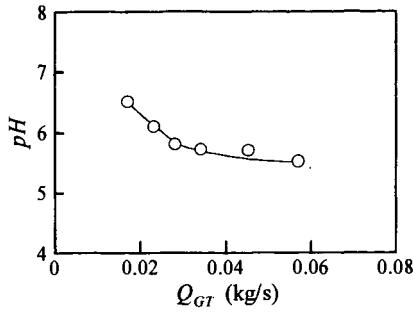Fig. 4 Superficial velocity of liquid phase in the riser as a function of gas injection rate.

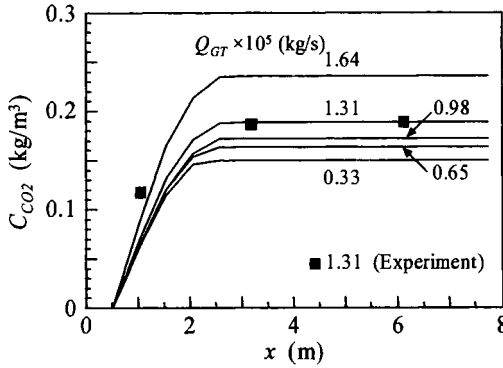Fig. 5 Acidity of CO_2 solution discharged from the laboratory P-GLAD.

Fig. 6 Computational results on CO_2 concentration in solution compared with experimental ones.

q_g represents the rate of dissolution, J_l [$= (1 - \alpha)u_l$] the superficial velocity of liquid phase, α the void fraction, u_l the velocity of liquid phase. D_T is the turbulent diffusion coefficient calculated from liquid phase flow of Reynolds number $J_l D/\nu$ using k-ε model, where ν is kinematic viscosity.

EXPERIMENTAL AND COMPUTATIONAL RESULTS

Defining CO_2 gas dissolution ratio as $R_D = Q_{CO2, dis}/Q_{CO2}$, the axial profile is plotted in Fig. 3, where $Q_{CO2, dis}$ represents the mass of CO_2 dissolved in liquid phase, and Q_{CO2} the mass of CO_2 included in injected gas. R_D rapidly increases for $z < 3$ m, and most of the CO_2 gas injected dissolves into the water phase in the section. The maximum values of R_D are 0.979, 0.955 and 0.964. P-GLAD shows satisfactory performance of CO_2 gas dissolution.
Superficial velocity of liquid phase J_L, namely lifted water velocity, is shown in Fig. 4 as a function of gas injection rate Q_{GT}. J_L gradually increases with increase in Q_{GT} before 3×10^{-5}kg/s. After the value, J_L is almost saturated. In higher gas injection rate, it was observed that indissoluble gas remained at the top of the riser. As a result, saturation of J_L occurs owing to increase in friction loss there.
Acidity of CO_2 solution discharged from laboratory-scale P-GLAD is plotted in Fig. 5 as a function of gas injection rate. The acidity increases with increase in gas injection rate. The value of pH is in the range between 5.5 and 6.5 in the present investigation. The acidity is moderate. Besides the acidity is controllable by adjusting the gas injection rate.
Figure 6 shows computational results on CO_2 concentration in solution and comparison of them with those of the experiment. Computational results show a good agreement with the experimental ones. Therefore, our numerical modeling and computational scheme is reasonable.

COST ESTIMATE

Before cost estimate, we carried out experiments using a large-diameter-pipe loop (150mm in diameter). Large-scale structure and turbulence mechanism of bubbly flows in a large diameter pipe were obtained [Mudde & Saito, 2000]. We performed cost estimate of P-GLAD for 1,000MW fired power plant listed in Table 1 on the basis of above experimental and numerical results. Gas transportation plant, CO_2 capture and separation plant, and dimension of P-GLAD

Table 1 Dimension of fired power plant.

Generating capacity	1,000MW
Location	Seaside
Rate of CO_2 discharge	100kg/s (360ton/s)

Table 2 Gas transportation plant.

Compressor power	40,000kw
Compressor location	Power plant site
Length of pipeline	100km
Diameter of pipe	0.5m
Material of pipe	High-tension steel

Table 3 CO_2 capture and separation plant.

Method	PSA (1 stage)
Adsorption	Under atmospheric pressure
Degassing	Under vacuumed
Dewatering tower	ϕ12.5m×H36m×16units
Number of adsorption/degassing tower	ϕ6m×L40m×16units
Adsorption material for CO_2	Zeorite
Adsorption material for water	Activated aluminum + Zeorite

Table 4 Dimension of P-GLAD.

Riser	ϕ0.5m×H300m×90units, High-tension steel
Downcomer	ϕ0.5m×L10km×90units, Rain-forced FEP steel
Gas injection depth	200m
Releasing depth	1000m
Float	ϕ11.6m×W150m
Anchoring	Tension leg

Table 5 Cost estimate of P-GLAD and comparison of the cost with that of a usual method (direct release of liquid CO_2).

	P-GLAD (US$/ton-$CO_2$)	Usual (US$/ton-$CO_2$)
Capture & separation	26	43
Liquefaction	0	64
Transportation	30	7
Sequestration	12	12
Total	68	126

are listed in Table 2 to Table 4, respectively. We estimated a total cost of the ocean sequestration by P-GLAD considering construction, operation, labor cost (in Japan), land cost (in Japan), tax (in Japan), interest and a price reduction. The result is summarized in Table 5.

Total cost of P-GLAD is a half of that of a usual method. Economical feasibility of P-GLAD is very higher than that of a usual method such as direct release of liquid CO_2 into intermediate depth water.

CONCULSION

We discussed performance and characteristics of P-GLAD (Progressive Gas Lift Advanced Dissolution system) experimentally and numerically. We obtained P-GLAD has satisfactory performance as an ocean sequestration system of low-purity CO_2 gas. On the basis of these results, we performed cost estimate of a total system of P-GLAD. P-GLAD showed highly economical feasibility.

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